Ceylon Journal of Science 52 (2) 2023: 209-217

RESEARCH ARTICLE

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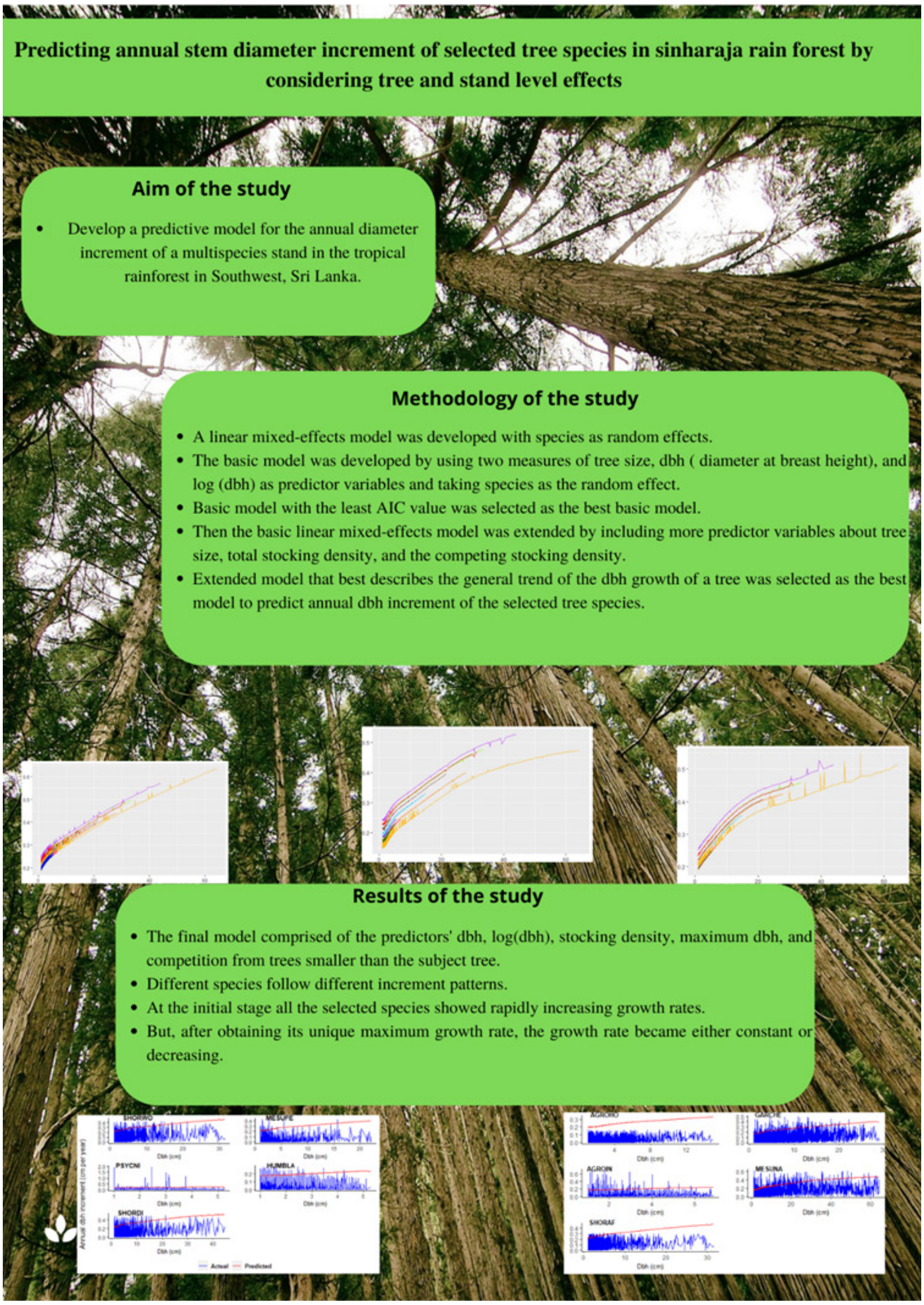

Highlights

- Different species follow different increment patterns.
- At the initial stage, all the selected species showed rapidly increasing growth rates.
- After achieving its unique maximum level, the growth rate became either constant or decreased.
- The best fitted linear mixed effect model can be used to predict the annual diameter increment of any selected tree species.

Ceylon Journal of Science 52 (2) 2023: 209-217
DOI: http://doi.org/10.4038/cjs.v52i2.8017

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Predicting annual stem diameter increment of selected tree species in Sinharaja rain forest by considering tree and stand level effects

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Received: 26.07.2022; Accepted: 27.04.2023

Abstract: Information on the diameter increment of tree species is important for developing a sustainable forest harvesting plan and for reforestation. Fitting a forest growth model for diameter increment can be utilized to get the information. The objective of this study was to develop a predictive model for the annual diameter increment of a multispecies stand in the Sinharaja Rain Forest in Sri Lanka. To fulfill this objective, four linear mixed-effect models were fitted to predict the annual diameter at breast height (dbh) increment of trees by using dbh, the natural logarithm of dbh, and species as a random effect. The model that contained random coefficients for the intercept term, dbh and log (dbh) were selected as the best-fitted model based on the Akaike Information Criterion (AIC) value and the likelihood ratio test. Then, the best-fitted model was expanded by adding other subsequent variables that describe the effects of competition from surrounding trees, and a size structure component, which is the maximum dbh. The final model comprised of this information dbh, log(dbh), stocking density, maximum dbh, and competition from trees smaller than the subject tree. Using the best-fitted final model, the annual dbh increment of the 10 selected abundant species was calculated. It was noted that all the selected species have growth rates that increase rapidly at the initial stage, and then reach its unique maximum growth rate. These increment patterns reflected that different species followed different annual dbh increment patterns. Therefore, this final model can be consolidated into an effective empirical model to project the future growth of a tropical rainforest.

***Keywords*:** Diameter increment; mixed-effect model; diameter at breast height (dbh); empirical model; random effects

INTRODUCTION

The diameter increment of a tree species is an important stand attribute that is used for understanding vegetation structure and estimation of the stock of above-ground biomass. Further, the diameter increments and growth patterns for individual trees are important tools for forest management primarily for (i) selecting tree species for logging; (ii) selecting tree species for protection; (iii) estimating cutting cycles, and (iv) prescribing silvicultural treatments (Silva *et al*., 2002). Individual-tree diameter growth models are also used to predict tree diameter increment in a stand, and they are one of the most important inputs for many individual-tree-based growth and yield models.

Generally, diameter growth models are commonly developed using either potential growth-based or potential growth-independent approaches (Subedi and Sharma, 2011). In the potential growth-based model diameter growth is modelled as a product of potential growth and a competition modifier function while in a potential growth-independent model, is expressed as a function of tree attributes, site characteristics, and measures of competition among individual trees.

In tropical forests, the size attribute is always more important than age to describe the dynamics of natural forests, especially because age is difficult to measure accurately (Silva *et al*., 2002). However, despite the difficulties of measuring the total tree height of tropical trees, diameter at breast height (DBH) has become the most important variable for allometric equations. Moreover, the prediction of the diameter increments of tree species in a tropical rainforest is a challenging venture due to an inadequate number of observations or unavailability of observations. Rahman *et.al* (2016) developed a linear mixed effect model to predict the annual stem diameter increment of major tree species in mixed dipterocarp forests in Semangkok Forest Reserve in Peninsular Malaysia by using tree-level and stand-level effects. Furthermore, Maleki *et al.* (2015) investigated the effect of individual tree competition on the diameter growth of Silver Birch in Estonia. They have devised non-spatial and spatial indices (combined with neighbour selection methods) separately into a growth model as a predictor variable to assess the ability of the diameter growth model before and after adding competition measures. A multilevel linear mixed model was used by Calama *et al.* (2005) for the diameter increment of stone pine in Spain. However, none of the studies has produced an annual diameter increment model for mixed dipterocarp forest in Sri Lanka. Therefore, the objective of this study is to develop a predictive model for the annual diameter increment of a multispecies stand in the tropical rainforest in Southwest, Sri Lanka.

MATERIAL AND METHODS

Site Description

The data used for this study were gathered from a plot located in the southwestern part of Sinharaja. The plot is in an undisturbed part of the forest at 6^0 24'N, 80^0 24'E which

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was 25ha in the area with dimensions of 500m × 500m. This plot consists of a central valley bounded by two slopes, one steeper and higher facing southwest and reaching up to 575m, and the other less steep facing northeast and extending up to about 505m.

In 1994, all individual trees with dbh > 1cm in the 25ha plot were enumerated. All these trees were tagged, and information was collected. Census was taken at regular intervals and the dataset used for the analysis was derived by combining four censuses from 1994, 2001, 2008, and 2013. Only trees that survived at all four censuses were used for predicting the annual dbh increment analysis. All trees with a diameter at breast height (dbh) ≥ 1cm were selected for the analysis. In the data cleaning process, the outliers identified as the trees showing large positive (> 99th percentile) dbh values from the dataset were excluded. Out of the remaining trees, trees that showed negative dbh increments were also excluded. A total of 190,021 trees were in the final dataset that belongs to 224 species. Among them, the 10 most abundant species (species with the highest number of individuals) in the plot were selected to visualize the annual dbh increment (Table 1). Then, the annual dbh increment values less than the three-sigma upper limit (mean + (3 × standard deviation)) of each species in the selected 10 species were used to illustrate the growth pattern among species. The three-sigma upper limit that follows normal distribution was set in terms of quality control of the analysis.

Data Structure

The predictor variables can be categorized as tree-level and stand-level attributes. The stand-level attributes were measured that represent size structure: maximum dbh (cm) and stocking density.

Under stocking density,

(i) Stand Basal Area (SBA) = $\sum (\pi \times dbh_i^2 / 40000$, and

(ii) Stand Density Index (SDI) = $\sum (dbh_i /25.4)^k$, k = 1.6, 2.0, 2.6

assuming maximum size-density slopes of 1.6, 2.0 and 2.6 were used as the predictor variables.

The tree-level attributes were measured that represent tree size: dbh, the natural logarithm of dbh, and the following competition indices,

(i) Competing Stand Basal Area (SBA_C) and

(ii) Competing Stand Density Index (SDI_C) assuming maximum size-density slopes of 1.6, 2.0 and 2.6.

The competing stand basal area in a plot can be calculated using several non-spatial indices as below (Maleki K *et al.,* 2015):

(i) $BA\text{-}g_j$ competing index - the sum of the basal area (*g)* of the neighbouring trees *j* for a subject tree *i* ($m^2\ ha^{-1}$);

(ii) *BAL* - the sum of the basal area of trees larger than the subject tree ($m^2\ ha^{-1}$);

(iii) *BAr* – the sum of the *g* neighbours divided by the subject tree *g* in the plot (ha^{-1}).

(iv) *BALr* - the ratio of *BAL* to the cumulative basal area of the plot

Trees smaller than the subject tree were assumed to be competing with the subject tree for growing space. The calculation of SDI_C was based on the maximum size-density concept and the contribution of individual trees to total SDI (Reineke, 1933; Long and Daniel, 1990). The slope of the maximum size-density line is represented by the exponent. When the dbh >25.4cm, a higher maximum size-density slope confers a greater value while it confers a lower value if dbh < 25.4cm. All values become equivalent when dbh = 25.4cm. The slope of 1.6 is consistent with Reineke's (1933) original results for many species, and the slope of 2.0 implies that SDI and stand basal area are equivalent (Rahman *et al*., 2016).

Model Selection and Statistical Analysis

Instead of developing the fixed-effects model, a linear mixed-effects model was used with species as random effects. The following are the advantages of the linear mixed-effect model. (i) The model form is common to all species, with slight perturbations to each parameter arising from the random species effect, (ii) All data are used in a single estimation algorithm, (iii) In a simulation context varying level of resolution concerning species or species grouping can be accommodated by the same equation (Rahman *et al*., 2016). Study designs leading to data sets that may be appropriately analyzed using linear mixed-effects models (LMM) include (i) studies with clustered data, such as students in classrooms, or experimental designs with random blocks, and (ii) longitudinal or repeated-measures

Table 1: Ten most abundant species in the selected plot.

Species Code	Species	No. of trees in the plot	As a percentage of the total no. of trees in the plot (%)
SHORAF	*Shorea affinis*	4611	0.021
SHORWO	*Shorea worthingtonii*	5075	0.023
PSYNCNI	*Psychotria nigra*	5256	0.023
MESUFE	*Mesua ferrea*	5545	0.025
AGROHO	*Agrostistachys hookeri*	6461	0.029
SHORDI	*Shorea disticha*	6526	0.029
GARCHE	*Garcinia hermonii*	7493	0.033
MESUNA	*Mesua nagassarium*	13660	0.061
AGROIN	*Agrostistachys intramarginalis*	16916	0.075
HUMBLA	*Humboldtia laurifolia*	21449	0.096

studies, in which subjects are measured repeatedly over time or under different conditions. The general equation of the linear mixed-effects model is given as $Y = X_i + Z_i b_i + \in_i$

The matrices X_i and Z_i represent the i^{th} fixed and random effects, respectively. The vector β describes the effect of covariates on the mean/expectation of the outcome, while b_i is the vector random effects for unit *i*. ϵ_i is the vector of the i^{th} residual.

Application of the Basic Model

The basic model was developed by using two measures of tree size, i.e., dbh, and log (dbh) as predictor variables and taking species as the random effect. The response variable was the annual diameter increment for each tree. Annual diameter increment was calculated as the difference between dbh size at the start and end of the growth period, divided by the period (in years) between measurements. Four basic models were developed by applying the random coefficient at the intercept terms and/or dbh and/or natural logarithm of dbh (Table 2). Then, the four basic models were compared using Akaike Information Criterion AIC values and likelihood ratio statistical test.

Selection of Predictor Variables

As the next step, the basic linear mixed-effects model was extended by including more predictor variables about tree size, total stocking density, and the competing stocking density (Table 3).

These predictors represented the effects of tree size (dbh and the natural logarithm of dbh), competition, stand density, and indicators of size structure. The natural logarithm has the desirable property of allowing a peaking behavior and asymptotic approach to zero as tree size increases towards a maximum (Rahman *et al*, 2016).

Increasing stand density has a negative influence on the diameter increment. Therefore, an increase in dbh increment can be expected with a reduction in stand density. Competition based on competing stocking density below gives the expected positive sign parameters or effects on dbh growth (Rahman *et al*, 2016). The maximum dbh of a tree implied that the growth of a given tree is lesser when maximum dbh is larger.

Assessment of Growth Behavior

The annual dbh increment as implied by the final model was examined for 10 selected species. The main aim of this study was to demonstrate the dbh increment pattern of different species over different predictor variables. The statistical data analysis was performed using R software version 3.6.1 (2019) with the *nlme* package in R to fit the linear mixed-effects models (Pinheiro *et al.,* 2012).

RESULTS AND DISCUSSION

Statistical Significance of the Basic Model

Table 4 shows the estimates of parameters and AIC values of each basic model given in Table 2. According to the results, Model 4 has the lowest AIC. The results of likelihood ratio test (Table 5) also indicated that Model 4 differs from other basic models. Based on these results, Model 4 was selected as the best fitted basic model.

Table 2: Four types of basic linear mixed-effects models tested.

Model	Linear mixed-effects models
1	sqrt (dinc + 0.01)$_{ij}$ = $(\alpha_0 + \delta_{0i}) + \alpha_1 dbh + \alpha_2 \log(dbh) + \varepsilon$
2	sqrt (dinc + 0.01)$_{ij}$ = $\alpha_0 + \delta_{0i} + \alpha_1 dbh + (\alpha_2 + \delta_{2j})\log(dbh_{ij}) + \varepsilon$
3	sqrt (dinc + 0.01)$_{ij}$ = $\alpha_0 + \delta_{0i} + (\alpha_1 + \delta_{1i})\, dbh_{ij} + \alpha_2 \log(dbh) + \varepsilon$
4	sqrt (dinc + 0.01)$_{ij}$ = $\alpha_0 + \delta_{0i} + (\alpha_1 + \delta_{1i})\, dbh_{ij} + (\alpha_2 + \delta_{2j})\log(dbh_{ij}) + \varepsilon$

dinc= Annual dbh increment and others are parameters that need to be estimated.

Table 3: Expanded linear mixed-effects models for predicting periodic annual diameter increment.

Model	Linear mixed-effect model
5	sqrt(dinc+0.01)$_{ij}$= $\alpha_0 + \delta_{0i} + (\alpha_1 + \delta_{1i})\, dbh_{ij} + (\alpha_2 + \delta_{2j})\log(dbh_{ij}) + \alpha_3\, SBA + \alpha_4 dmax + \alpha_5 SBA_c + \varepsilon$
6	sqrt(dinc+0.01)$_{ij}$= $\alpha_0 + \delta_{0i} + (\alpha_1 + \delta_{1i})\, dbh_{ij} + (\alpha_2 + \delta_{2j})\log(dbh_{ij}) + \alpha_3\, SDI_{1.6} + \alpha_4 \mathrm{dmax} + \alpha_5 SDI_{c1.6} + \varepsilon$
7	sqrt(dinc+0.01)$_{ij}$= $\alpha_0 + \delta_{0i} + (\alpha_1 + \delta_{1i})\, dbh_{ij} + (\alpha_2 + \delta_{2j})\log(dbh_{ij}) + \alpha_3 SDI_{2.0} + \alpha_4 \mathrm{dmax} + \alpha_5 SDI_{c2.0} + \varepsilon$
8	sqrt(dinc+0.01)$_{ij}$= $\alpha_0 + \delta_{0i} + (\alpha_1 + \delta_{1i})\, dbh_{ij} + (\alpha_2 + \delta_{2j})\log(dbh_{ij}) + \alpha_3\, SDI_{2.6} + \alpha_4\, \mathrm{dmax} + \alpha_5 SDI_{c2.6} + \varepsilon$

increment, SBA_c = competing stand basal area, dmax = maximum dbh, SDI_c = competing stand density index

Table 4: Parameter estimates and standard errors for four basic linear mixed effects models.

Parameter estimate	Model 1		Model 2		Model 3		Model 4	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
α_0	0.20984	0.00482	0.21371	0.00558	0.21258	0.00536	0.21111	0.00481
α_1	0.00608	0.00010	0.00376	0.00012	0.00109	0.00072	0.00642	0.00067
α_2	0.02282	0.00078	0.02926	0.00304	0.03942	0.00101	0.02319	0.00483
AIC	-203268.8		-206947.2		-206252.9		-207829.7	

SE = standard error, all parameters are significant at p = 0.05; the basic model refers to the predictors comprising only dbh as the variable.

Table 5: Comparison of four basic models by the Likelihood Ratio (LR) test for periodic annual diameter increment.

Model	df	LR Test	
		Test	LR
1	5		
2	7	1 vs 2	3682.4***
3	7	2 vs 3	
4	10	3 vs 4	1582.8***

df = Degrees of freedom, *** = significant at $p < 0.05$

Statistical significance of the competing stand basal area

In Table 6, the Spearman's rank correlation coefficients between the tree diameter growth and non-spatial competing indices used to calculate competing stand basal area were presented.

Table 6: The Spearman's rank correlation coefficients between tree diameter increment and competition indices.

Non – spatial indices	**Correlation Coefficient**
BA-g	-0.0212446
BAL	-0.259415
BAr	-0.2570353
BALr	-0.1772028

The results indicate that all four competing indices have negative correlation coefficients. This implies that when the competing stand basal area increases, the tree diameter growth decreases. When comparing the correlation coefficients, the *BAL* has the highest negative correlation coefficient. Therefore, *BAL* was selected as the competing index for calculating the competing stand basal area.

Statistical Significance of the Extended Model

Table 7 presents the parameter estimates and AIC values of Model 5 – Model 8. The AIC values of these models and the best fitted basic model (Model 4) are compared to identify the most suitable model. According to the results, Model 8 with the predictor variables SDI for the maximum size-density slope of 2.6 has the lowest AIC value.

However, in Model 8, log dbh variable is not significant since the corresponding p-value is greater than 0.05. Then, the next three models will be selected based on their AIC values. Since the AIC values of models 5, 6, and 7 are very close, all the three models were used to predict the annual dbh increments for the selected 10 species.

Figure 1 shows the predicted annual dbh increments for the selected 10 species based on model 5.

According to figure 1, predicted annual dbh increments are almost linearly increasing. This implies that when the dbh of a tree increases, the corresponding annual dbh increment is also increasing.

Figure 2 shows predicted annual dbh increments under model 6. According to this figure, the predicted dbh increments increase until they reach their maximum value and then decrease or remain constant.

According to figure 3, predicted annual dbh increments are increasing under model 7.

The general trend of the dbh growth of a tree shows primarily three stages: (i) juvenile period where growth is rapid and often exponential; (ii) a long period of maturation where the trend is linear with a tendency toward

Table 7: Parameter estimates, standard errors, and AIC values for the four expanded linear mixed-effects models for periodic annual diameter increment.

Parameter estimates	**Model 5**		**Model 6**		**Model 7**		**Model 8**	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
α_0	0.34855	0.014247	0.18855	0.007989	0.18500	0.007949	0.16722	0.007951
α_1	0.00303	0.000688	-0.00169	0.000817	-0.00248	0.001115	0.01721	0.000948
α_2	0.02283	0.004962	-0.02156	0.005657	0.01703	0.004942	0.00039	0.005007^n
α_3	-0.01273	0.003085	-0.00005	0.000008	-0.00004	0.000006	-0.00002	0.000004
α_4	0.00139	0.000211	0.00195	0.000220	0.00178	0.000218	0.00174	0.000217
α_5	0.00455	0.000323	0.00002	0.000001	0.00002	0.000003	-0.00004	0.000002
AIC	-208086.7		-208082.3		-207972.1		-208161	

SE = standard error, n = not significant at $p < 0.05$, all other parameter estimates showed significant p-values; model equations given in Table 3 curvilinearity and (iii) old age where growth is nearly asymptomatic (Wainwright and Mulligan, 2013). So, any predicting model should depict the above three stages of the dbh growth of a tree.

Therefore, Model 6 illustrates the annual dbh increment of a tree more accurately than the other two models. Thus, Model 6 was selected as the best fitted model to predict the annual dbh increment of the selected tree species. The maximum size-density slope of 1.6 is consistent with Reineke's (1933) results for many species, while the slope of 2.0 implies a fixed basal area (Abd Rahman *et al.,* 2016). These results imply that the annual diameter increment of trees in the Sinharaja rain forest can be well explained by a lower maximum size-density slope value.

The scatter plots of dbh, the natural logarithm of dbh, and other selected predictor variables ($SDI_{1.6,}$ dmax, $SDI_{c1.6}$) of model 6 do not show any pattern implying that there is no bias to the residuals (Figure 4). Therefore, this linear mixed effect model (Model 6) can be used to predict the annual diameter increment of tree species for the selected species in Sinharaja Forest Dynamic Plot.

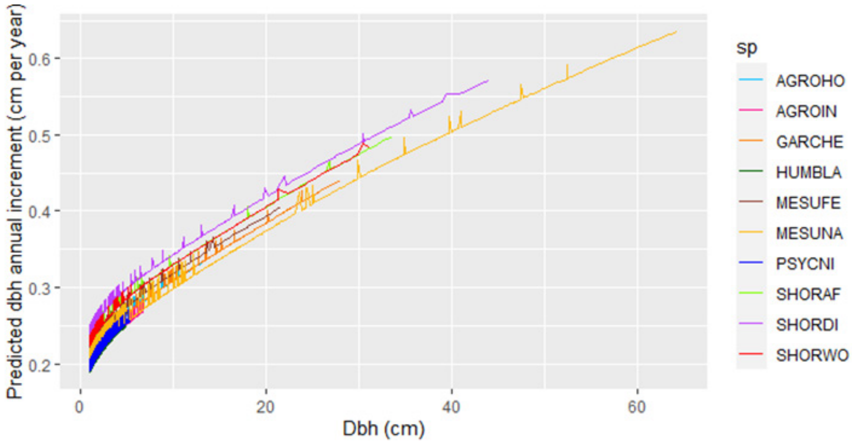

Figure 1: Predicted annual diameter at breast height (dbh) increment by Model 5 for selected tress species in relation to dbh.

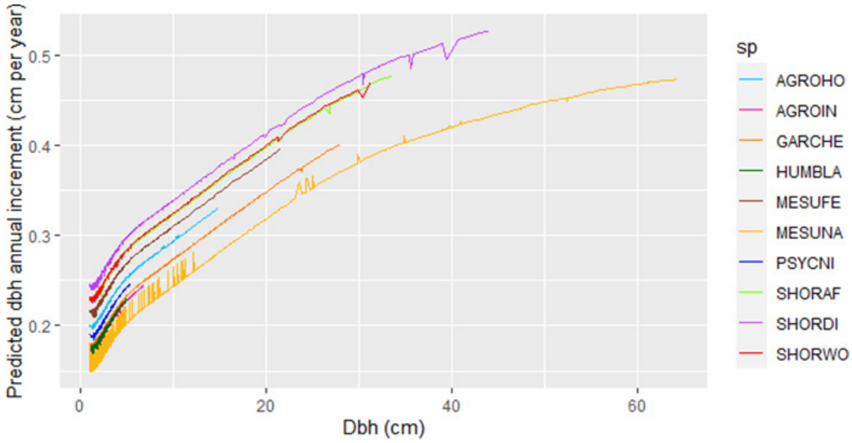

Figure 2: Predicted annual diameter at breast height (dbh) increment by Model 6 for selected tress species in relation to dbh.

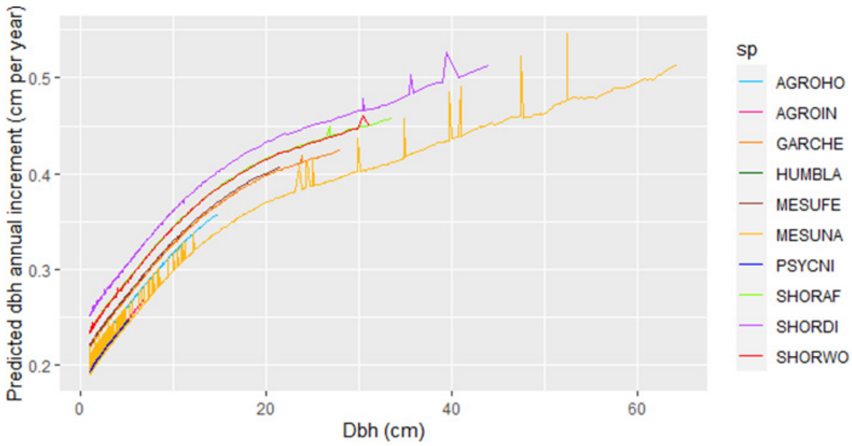

Figure 3: Predicted annual diameter at breast height (dbh) increment by Model 7 for selected tress species in relation to dbh.

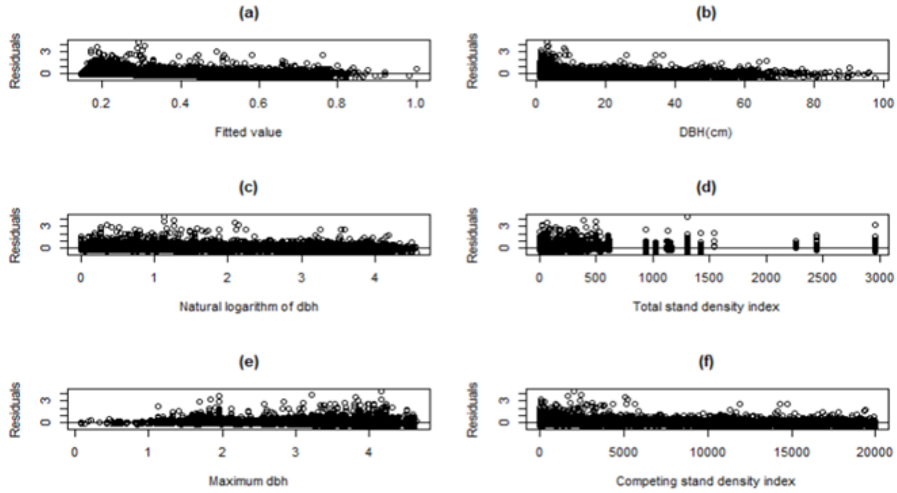

Figure 4: Scatterplots of residuals vs (a) predicted dbh increment, (b) dbh, (c) natural logarithm of dbh, (d) total stand density index (SDI), (e) maximum dbh and (f) competing stand density index (SDIC1.6) using Model 6.

Assessment of Growth Behavior

Figure 5 represents annual dbh increments for the dbh ranging from 1 cm to 10cm for the selected 10 species, and Figure 6 shows the annual dbh increment for the dbh ranging from 10cm to 65cm for the same selected 10 species.

Different species follow different annual dbh increment patterns (Figure 5 and Figure 6). Therefore, these tree species have different maximum annual dbh increment rates. According to Figure 5, in the beginning, all the species show a constant annual dbh increment. Thereafter, until the dbh reaches its maximum dbh increment rate, these increments show rapid increment (Figure 6).

However, after reaching its unique maximum growth rates, the growth rate becomes either constant or decreased (Figure 6). Among the 10 species, "*SHORDI*" showed the highest dbh increment rate, across the dbh class, obtaining its maximum dbh increment rate at 44.8cm dbh. *MESUNA* showed the lowest dbh increment rate and obtained its maximum at 64.4cm with a higher increment rate. Another tree species, *GARCHE* reached the maximum at 28.15cm dbh with a much slower rate (Figure 6).

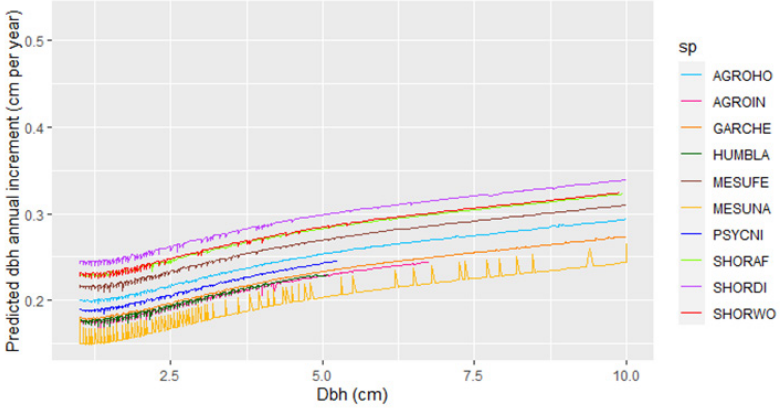

Figure 5: Predicted annual diameter at breast height (dbh) increment by Model 6 for selected tress species in relation to dbh ranging from 1 cm to 10cm.

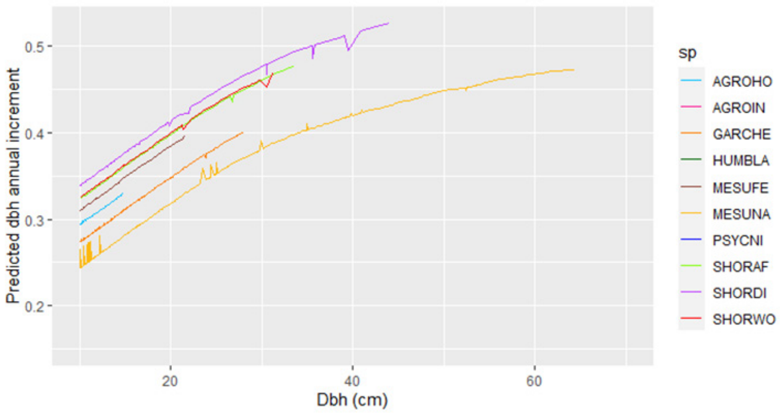

Figure 6: Predicted annual diameter at breast height (dbh) increment by Model 6 for selected tress species in relation to dbh ranging from 10cm to 65cm.

The actual verses predicted annual dbh increment of the species *AGROHO, GARCHE, AGROIN, MESUNA*, and *SHORAF* are shown in Figure 7. Also, Figure 8 presents the actual verses predicted annual dbh increment of the species *SHORWO, MESUFE, PSYCNI, HUMBLA,* and *SHORDI.*

According to figure 7, the predicted annual dbh increment rate for *MESUNA* and *GARCHE* falls through the actual dbh increment while the predicted annual dbh increment lies above the actual dbh increment for the species *AGROHO*. The predicted annual dbh increment of *SHORAF* and *AGROIN* slightly fits the actual annual dbh increment.

According to figure 8, the predicted annual dbh increments for all species slightly fit the actual dbh increment patterns. Further, the predicted annual dbh increment rates of the species show increasing behavior at the beginning and after reaching their maximum rate, those rates remain constant or decrease. However, the actual annual dbh increment rates do not show a clear pattern and fluctuate often.

Note that the predicted lines are almost linear while the actual values are highly varying in both Figures 7 and 8. The reason for this volatility may be some other related variables are missing in the fitted model which affect the annual dbh increment of a tree species. For example, the increment rate may be affected by internal conditions such as genetic, physiological factors, and external conditions such as climatic, edaphic, and biotic factors. Therefore, by adding the relevant variables, this model can be further developed.

CONCLUSION

A linear mixed effect model for annual diameter increment was illustrated using data from 10 selected tree species in the Sinharaja rain forest. The final model comprised of the predictors' dbh, log(dbh), stocking density, maximum dbh, and competition from trees smaller than the subject tree. These predictors reflected tree size, competition, and stand size variability. As species random effects were used in the linear mixed-effect model, the final model can be used to predict the annual diameter increment of any tree species. According to the results, different species follow different increment patterns. At the initial stage all the selected species showed rapidly increasing growth rates. But, after

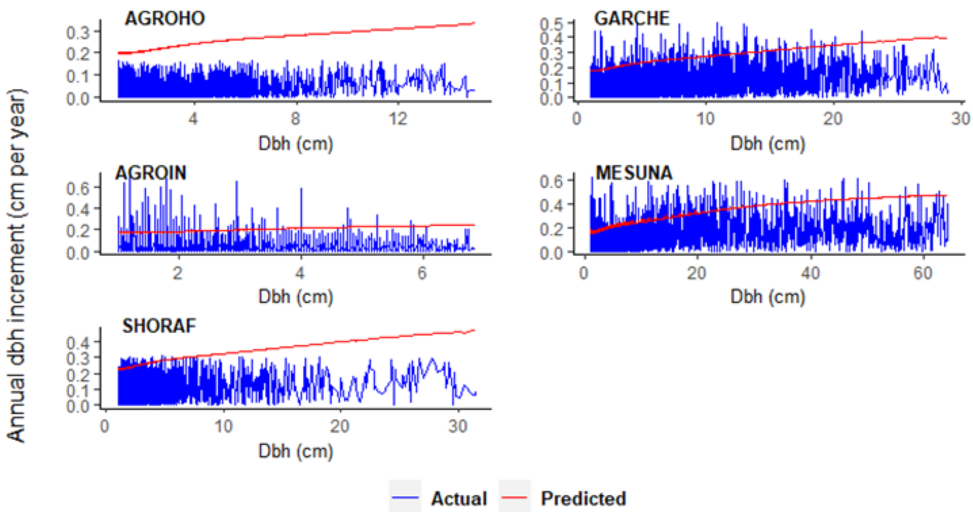

Figure 7: Actual vs Predicted annual dbh increment for AGROHO, GARCHE, AGROIN, MESUNA, and SHORA.

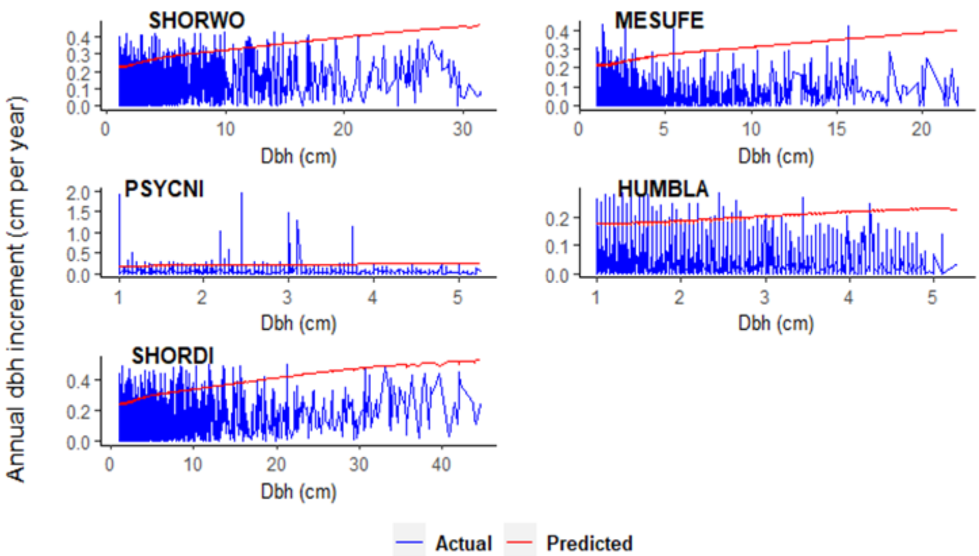

Figure 8: Actual vs Predicted annual dbh increment for SHORWO, MESUFE, PSYCNI, HUMBLA, and SHORDI tree species.

obtaining its unique maximum growth rate, the growth rate became either constant or decreased. This final model can be consolidated into an effective empirical model to project the future growth of a tropical rain forest. This model can be further improved by applying the non-linear mixed-effects approach and by including climatic, edaphic, and biotic factors in the model. However, the correlation among trees within the plot was not addressed in the analysis.

ACKNOWLEDGEMENT

The authors would like to acknowledge the guidance and encouragement provided by all the faculty members in the Department of Statistics and Computer science in Faculty of Science at University of Peradeniya.

STATEMENT OF ANY CONFLICTS OF INTEREST

The authors declare no competing interests.

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Supplementary Information

Supplementary Table 1: Summary statistics for the data used to develop the periodic annual increment in diameter at breast height (dbh) model for multispecies stand in Sinharaja rainforest

Variable	Variable code	Mean	SD	Min	Max
Annual dbh increment (cmyear^{-1})	dinc	0.066	0.198	0	21.446
dbh (cm)	dbh	3.906	5.956	1	97.6
Stand basal area (m^2 ha^{-1})	SBA	0.882	1.655	4.155e-06	6.525
Stand density index (SDI) at slope 1.6	$SDI_{1.6}$	509.926	739.086	0.007	2960.765
SDI at slope 2.0	$SDI_{2.0}$	435.076	816.387	0.002	3218.883
SDI at slope 2.6	$SDI_{2.6}$	458.951	1066.796	0.000320	4160.74
Competing basal area (m^2)	SBA_c	34.317	3.719	0.030	36.565
Competing SDI at slope of 1.6	$SDI_{c1.6}$	1964.131	2686.899	0	19958.92
Competing SDI at slope of 2.0	$SDI_{c2.0}$	932.453	1808.206	0	18016.45
Competing SDI at slope of 2.6	$SDI_{c2.6}$	409.121	1359.463	0	19457.21
Maximum dbh (cm)	dmax	25.877	21.344	1.1	104.25

SD = standard deviation, MIN = minimum, MAX = maximum

Supplementary Table 2: Summary statistics for diameter at breast height (cm) of tree species used in the fitting dataset

Species code	No. of trees	Mean	SD	Min	Max
SHORAF	4057	4.395	5.550	1	33.65
SHORWO	4286	3.651	4.339	1	31.4
MESUFE	5634	2.841	2.719	1	22.1
PSYCNI	5372	2.287	0.923	1	5.25
HUMBLA	22337	1.797	0.714	1	5.4
SHORDI	7075	3.431	4.869	1	44.8
AGROHO	6439	3.016	2.202	1	15
GARCHE	7581	6.257	5.273	1	28.95
AGROIN	17306	2.363	1.148	1	6.85
MESUNA	14231	5.419	9.464	1	64.4

SD = standard deviation, MIN = minimum, MAX = maximum